3.8. Submarine canyons in the Catalan Sea (NW Mediterranean): megafaunal biodiversity patterns and anthropogenic threats

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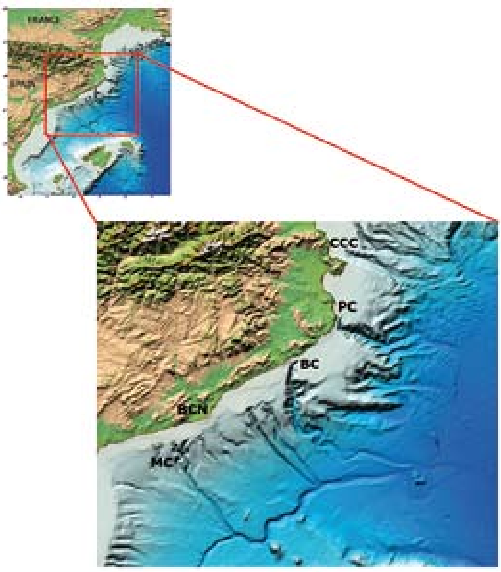

Fig. 1:

Shaded relief general bathymetry map of the northwestern Mediterranean Sea. The insert provides a detail of the central and north Catalan margin showing the canyons considered in this case study. BCN, Barcelona; BC, Blanes canyon; CCC, Cap de Creus canyon; MC, Merenguera canyon; PC, La Fonera or Palamós canyon. Catalano-Balearic Sea map modified from: 2005, Catalano-Balearic Sea – Bathymetric chart, http://www.icm.csic.es/geo/gma/MCB/index.htm. Bathymetric data from Canals *et al.*, 2004b.

INTRODUCTION: GEOMORPHOLOGY AND PHYSICAL OCEANOGRAPHY

The continental margin of the Catalonia is crossed by several submarine canyons of different evolutionary history (Fig. 1) (Canals *et al.*, 2004a). The main characteristic of the circulation pattern on the Catalan coast is a slope current referred to as the Northern current, which is associated with a shelf–slope density front that in this area flows mainly towards the southwest (Font *et al.*, 1988). This baroclinic current separates the low-salinity shelf waters from the denser open-sea saline waters.

The hydrodynamics in submarine canyons basically depend upon several forcing conditions in the region such as general circulation, bottom morphology and atmospheric regime. Forcing conditions differ among canyons and can give different responses. Most of the particulate matter transferred from the shelf through submarine canyons comes from continental runoff and/or resuspension (e.g., during storms or cascading events) and coastal biological productivity. Such transfers are conditioned by particulate matter inputs, topography and hydrodynamics outside and inside the canyon. Within the canyon, the hydrodynamic pattern may lead to the retention and/or resuspension of particulate matter, which can be affected by several sedimentation and erosion cycles before reaching a final fate (Puig and Palanques, 1998; Palanques *et al.*, 2006a; Puig *et al.*, 2008). Besides the natural processes, fishing activity carried out within their confines at the present time can play an important role in the dynamics of the canyon systems.

In this chapter we describe some of the outcomes of Spanish national and European research projects in relation to the life history, distribution, biomass and composition (i.e. biodiversity) of benthic (i.e. bottom living) vertebrate and invertebrate species in different Catalan Sea canyons and open slope areas (western Mediterranean). These biological characterizations have been carried out in relation to bathymetric, geomorphologic and seasonal changes in habitat conditions within the northwestern Mediterranean Sea (Company and Sardà, 1997, 1998, 2000; Company *et al*. 2001; Aguzzi *et al.,* 2010a).

The main objective of this case study is to present a global and updated overview on the majority of available data in the Catalan area showing how the geomorphology of submarine canyons and the adjacent open slopes have an influence on the life-cycles of several bathyal species, which in some cases represent important fishery resources. Also, we will show how recruitment (i.e. the incorporation of juveniles into adult populations) of these species takes place in canyon heads. The presentation of up-to-date available data responds to the need to support initiatives of preservation and devoted management of the habitats present in these submarine canyons, mainly regarding commercial fisheries, a goal which has been pursued for several decades.

BIODIVERSITY PATTERNS

The rough topography of canyons has affected our ability to sample and study megafaunal communities until recently. Our knowledge is therefore limited. However, in the past decade, a number of studies have been conducted in the NW Mediterranean canyons, using both traditional gear such as otter and Agassiz trawls and new technologies such as ROVs (Remote Operated Vehicles). We present here data on deep-water (400-1500 m depth) megafaunal diversity from two canyons: the Merenguera canyon, just south of Barcelona, and the Blanes canyon, 60 km north of Barcelona (Fig. 1).

Merenguera canyon

The megafaunal communities in the upper part of the Merenguera canyon (450 m depth) were investigated and compared to those from the adjacent middle (650 m depth) and lower (1200 m depth) open slope during the RETRO project in 1991 and 1992 (Sardà *et al.*, 1994a; Company *et al*., 2003; Ramirez-Llodra *et al.*, 2008). The two shallower sites are visited daily by a specialized commercial trawl fisheries fleet, while the lower site has not been impacted by fisheries.

Decapod crustaceans and fish (Fig. 2) are the most abundant groups in the deep Mediterranean Sea, including canyons, accounting for most of the biomass (Company *et al*., 2004; Aguzzi and Company, 2010). In the Merenguera canyon and on the adjacent open slope, the biomass of decapod crustaceans (Sardà *et al.*, 1994a) and other invertebrates (Ramirez-Llodra *et al.*, 2008) was higher in the submarine canyon than on the open slope sites, while fish biomass was higher on the lower open slope (i.e. 1200 m depth). However, smaller species and juveniles of both decapod crustaceans and fish were most abundant in the canyon head (Sardà *et al.*, 1994a), suggesting that these sites can act as recruitment areas (Sardà *et al.*, 1994a, b; Stefanescu *et al.*, 1994).

The biodiversity studies conducted for non decapod-crustacean invertebrates showed that mollusks, echinoderms, polychaetes and cnidarians (Fig. 3) are the most speciose and abundant groups, with overall biodiversity (i.e., Shannon-Wiener index) higher in the canyon as compared to adjacent open slope (mudflat) areas. The biomass and abundance of most of the studied groups were lower on the middle open slope site, the most impacted by commercial

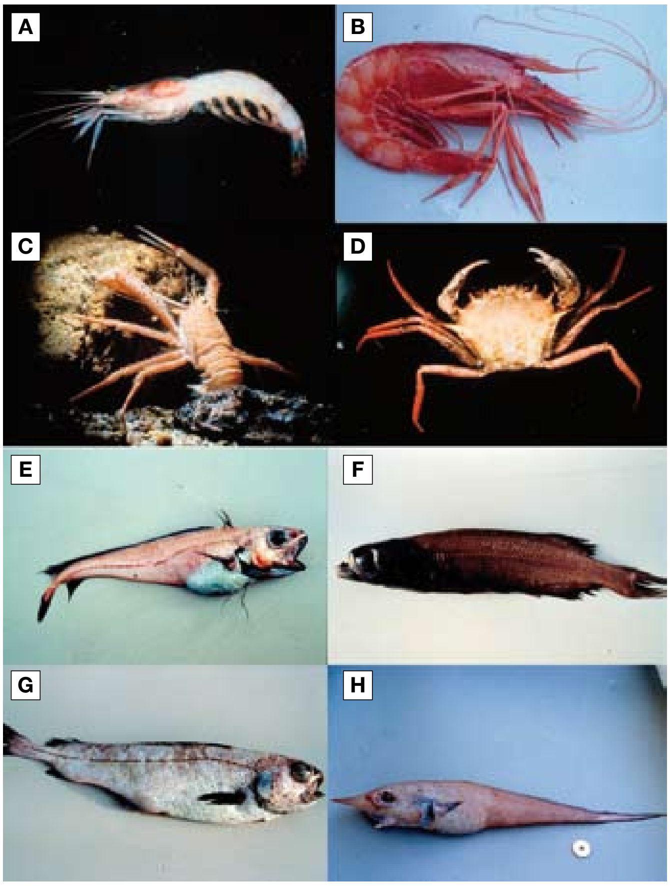

Fig. 2:

Common decapod crustaceans and fishes from the deep northwestern Mediterranean continental margin. A, the glass shrimp *Pasiphaea multidentata*; B, the deep-sea red shrimp *Aristeus antennatus*; C, the galathied squat lobster *Munida intermedia*; D, the deep-sea geryionid crab *Geryon longipes*; E, the deep-sea gadiform *Lepidion lepidion*; F, *Alepocephalus rostratus*; G, the deep-sea gadiform *Mora moro*; and H, the deep-sea grenadier *Trachyrincus scabrus*. (© L. Dantart).

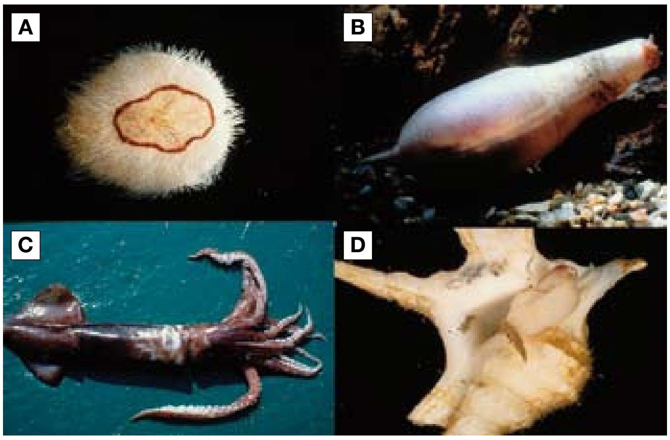

Fig. 3:

Invertebrate fauna found in the northwestern Mediterranean canyons. A, the irregular sea urchin *Brissopsis lyrifera*; B, the holothurian *Molpadia musculus*; C, the bathyal squid *Todarodes sagitattus*; and D, the mollusk *Aporrhais serresianus.* (© L. Dantart).

trawling activities. Furthermore, the upper part of the canyon and the middle open slope sites (i.e., 400 and 650 m depth) were dominated by echinoderms and mollusks, while the lower open slope site (i.e. 1200 m depth) was dominated by cnidarians and sponges. Although further detailed studies would be necessary in order to establish biodiversity patterns as a function of depth and other environmental or anthropogenic factors in and out of the canyon, it suggested that the higher abundance of sessile filter feeders (cnidarians and sponges) on the lower open slope site reflected a lack of physical disturbance from fishing. This factor should be considered in association with the enhanced hydrodynamic regime caused by the proximity of the canyon itself (Ramirez-Llodra *et al.*, 2008).

Blanes canyon

The Blanes canyon, one of the largest in the Catalan Sea (Canals *et al.*, 2004a), and the adjacent open slope, has been extensively studied for benthic species distribution and biodiversity patterns during two multidisciplinary Spanish research projects, RECS (400-900 m depth) and PROMETEO (900-1500 m depth), during the years 2003-2004 and 2008-2009, respectively.

The RECS project studied the distribution of biological communities in relation to changeable environmental patterns in three different continental margin sites: the canyon head (i.e., 364-585 m), the canyon wall (i.e., 402-603 m) and the open slope (i.e., 512-900 m). All these areas are exploited by the local Catalan trawl fleet, targeting the red shrimp *Aristeus antennatus*, one of the most highly appreciated fishery resources in the Mediterranean Sea (Sardà *et al.*, 2009). A total of 131 megabenthic species were identified, with decapod crustaceans and fishes being the most abundant groups, accounting for the 80% of the total biomass (Ramirez-Llodra *et al.*, 2010). The faunal composition of non-crustacean invertebrates was very different than that reported in the Merenguera area (south of Barcelona) at similar depths a decade before (see previous section). While 88 species of non-crustacean invertebrates were collected in the Merenguera area, dominated by mollusks and echinoderms, only 24 species were reported from the Blanes area. In this latter site, gastropods, bivalves and ophiuroids were absent, with the diversity and abundance of echinoderms comparatively much lower than in the Merenguera area. It has been suggested that the prolonged and intensive fishery activity (i.e. over six decades) in the Blanes area may partly explain the differences observed in the Merenguera site. Although no significant differences were observed in total abundance and biomass of megafauna between the three sites, the community structure of the open slope presented a lower species richness, lower diversity and lower evenness (i.e. low dominance of any species in respect to the whole community) and a higher degree of disturbance than that observed from the canyon head and canyon wall (i.e., the abundance curve lies above the biomass curve in the ABC plot) (Fig. 4). Taken altogether, these results suggest that, although there is a canyon effect on the community structure of benthic megafauna in the Blanes area, this may be modulated by differing fishing pressures (Ramirez-Llodra *et al.*, 2010).

The PROMETEO project studied biological communities and environmental patterns at 5 sites at different depths (i.e., 900, 1050, 1200, 1350 and 1500 m) on the Blanes canyon axis and on its adjacent western open slope. Because of the difficulty of sampling for megafauna with traditional sampling systems (i.e. towed nets, sledges or the Agassiz) within the narrow canyon axis, samples

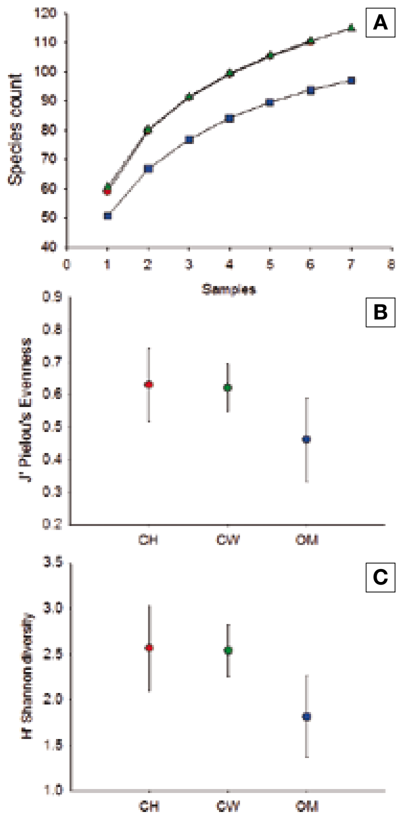

Fig. 4:

Diversity indices of megafaunal communities in the Blanes canyon and adjacent open slope (adapted from Ramirez-Llodra *et al.*, 2010). A, species accumulation plots; B, Pielou evenness; C, Shannon-Wiener diversity. CH and red dots: canyon head; CW and green dots: canyon wall; OM and blue dots: open slope.

were only collected at 900 and 1500 m depth. The comparative analysis of species accumulation curves (i.e. the potential maximum number of species present in a specific habitat) for the open slope and canyon showed differences. While the open slope curve almost showed a plateau, suggesting that this area is relatively well sampled, the canyon curve was still rising steeply, indicating that the canyon community has only been sampled partially (Tecchio *et al.*, submitted) (Fig. 5). A total of 115 species were collected from these sites, with decapod crustaceans and fishes being the most abundant groups. A peak of biomass and abundance was reported at 1200 m on the open slope. The factors causing this peak are presently still not understood, but results from Tecchio *et al.* (submitted) suggest that a combination of different ecological forcings on deeper-living species made them better adapted to a more stable, photon-absent and high pressure system. These species would be unable to compete with the more active shallower ones (i.e. from the middle slope above 900 m depth). For these reasons a transition zone (i.e. ecotone-like boundary) may occur at 1200 m depth, with high levels of biomass but lower diversity, compared to the upper and lower slope areas. Total abundance and biomass were not significantly different between the open slope and canyon axis sampled at the same depths (900 and 1500 m), but canyon diversity was higher and community structure different from that of the open slope (Tecchio *et al.*, submitted). Species such as the echinoid *Brissopsis lyrifera* (Fig. 3A) were only collected within the canyon and were most abundant at 1500 m depth. This is similar to the distribution of this species in the upper part of the Blanes canyon and open slope (Ramirez-Llodra

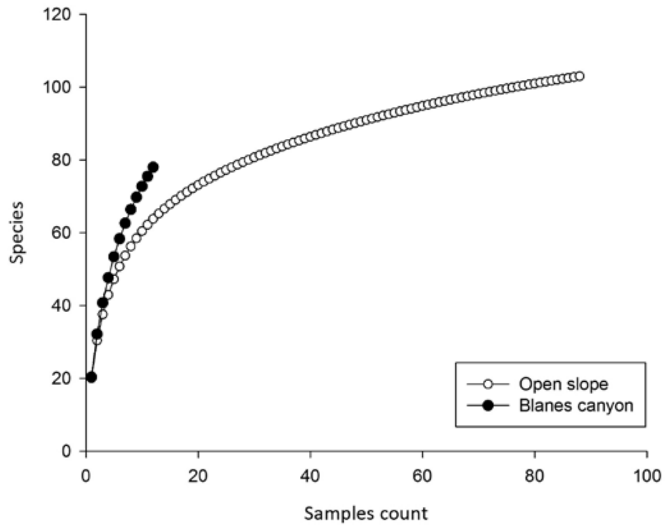

Fig. 5:

Species accumulation curves for the communities in the Blanes canyon (full circles) and adjacent open slope (open circles) (adapted from Tecchio *et al.*, submitted).

et al., 2010). On the contrary, *B. lyrifera* was very abundant in the Merenguera canyon and on the open slope, and fishermen report high quantities of this echinoid being previously collected in their trawl commercial gears. All this information, together with the fact that the Blanes canyon at 900 m depth is presently heavily impacted by commercial fishery, suggests a severely harmful effect of that commercial activity on benthic fragile species with low motility (e.g., the burrowing echinoid)(Ramirez-Llodra *et al.*, 2010; Tecchio *et al.*, submitted).

FISHERIES ISSUES

Fisheries on the Catalan coast related to submarine canyons: Cap de Creus, Palamós, Blanes, Arenys and Merenguera canyons

The Catalan continental margin supports an important commercial fishing activity related to the presence of several submarine canyons, from the north (i.e., Cap de Creus Canyon) to the south (i.e., the small canyons of the Ebro Delta area) (Fig. 1). The main target species of this extractive activity is a highly appreciated crustacean, the deep-sea red shrimp *Aristeus antennatus* (Risso, 1816). The annual average price in the fishery markets of this species is over 80 EU per kilo, but it can rise to 200 EU per kilo during the summer and Christmas season, this being one of the main reasons for the growing interest in this red shrimp by the Catalan fleet over the past 6 decades.

The populations of *A. antennatus* show seasonal migrations and its life-cycle is closely related to the geomorphology of the continental slope, characterized by the presence of submarine canyons (Sardà *et al.*, 1994b). Specialized fishing boats follow these seasonal movements around the canyon area. The fishing gear used by these boats is a benthic otter trawl, which is large in comparison to other traditional gears and can be operated by fishing vessels with 700–2000 HP engines. These bottom trawls have two heavy otter-boards that can spread as far as 100 m between them. The mouth of the net is 40–50 m wide, and the total length of the net is about 80–150 m. The sweeplines that connect the otter-boards to the net have a total length of 60–200 m. It is important to note that these fishing gears are much larger than those used near the coast.

Effects of dense shelf water cascading on the fisheries of the deep sea shrimp Aristeus antennatus

Dynamics of biological processes on the deep-sea floor are traditionally thought to be controlled on a seasonal scale by the vertical sinking of organic matter particles from more productive superficial photic layers, when photosynthesis occurs (Company *et al.*, 2003; Aguzzi and Company, 2010). The life histories of animals dwelling in the vast extensions of the deep-sea realm mainly rely on these sinking particles (Puig *et al.*, 2001; Company *et al.*, 2003). Despite a scenario of low productivity, the deep-sea areas sustain surprisingly large biomasses of predatory fish, crustaceans and other invertebrates (see Figs 2 and 3) (Tecchio *et al.*, submitted). However, the increase in deep-sea fisheries often leads to rapid depletion of demersal stocks after only a few years of exploitation. Among the over-exploited stocks worldwide, Mediterranean fisheries are considered a high priority for recovery. But surprisingly, some Mediterranean stocks have not collapsed. One of the most striking examples of this paradox is the deep-sea red shrimp *Aristeus antennatus*.

Vertical and seasonal low input of organic material to the deep-sea floor is widely accepted as the main source of nutrients for canyon ecosystems (Bahamon *et al.,* 2011). However, some studies have pointed out the influence of lateral particle transport from continental margins to deep-sea ecosystems, mainly following the path of the central axis of the submarine canyons (Puig and Palanques, 1998; Canals *et al.*, 2006; Martin *et al.*, 2006; Company *et al.*, 2008). At present, we know that a climate-induced phenomenon, such as the formation of dense shelf waters and their subsequent abrupt downslope fall through canyons (i.e. like a cascade phenomenon), affects the population of *A. antennatus* (Company *et al.*, 2008). The northwestern Mediterranean is one of the regions of the world where massive, open ocean, dense water formation occurs because of cooling and evaporation of surface waters during winter-time (Fig. 6). Concurrent with this phenomenon, coastal surface waters over the wide shelf of the Gulf of Lion also become denser than the underlying waters and cascade downslope, mainly through submarine canyons, until they reach their equilibrium depth (Canals *et al.*, 2006; Palanques *et al.*, 2006a; Puig *et al.*, 2008). In very dry, windy and cold winters, such as in 2005, cascading was exceptionally intense. Under these circumstances, dense shelf waters propagate along and across the continental slope, reaching depths >2000 m, generating a thermohaline and turbidity anomaly in the Western Mediterranean Deep Water which spreads over the entire northwestern Mediterranean basin (Fig. 7). Previous intense cascading events of dense shelf waters (i.e. those reaching the deep basin) were identified after the analysis of historical hydrographic data: they occurred in 1971, 1980, 1988 and 1999, therefore showing a periodicity of between 6 and 11 years (Fig. 8) (Bethoux *et al.,* 2002).

Strong downward currents associated with intense cascading events cause the disappearance of *A. antennatus* populations from their traditional fishing grounds, producing a temporary collapse in landings, as witnessed during winters of the years 2005 and 2006 (Fig. 6). Despite this first negative effect, landings increase between 2 and 4 years after these major cascade events, preceded by an increase of juveniles (i.e. recruitment). The

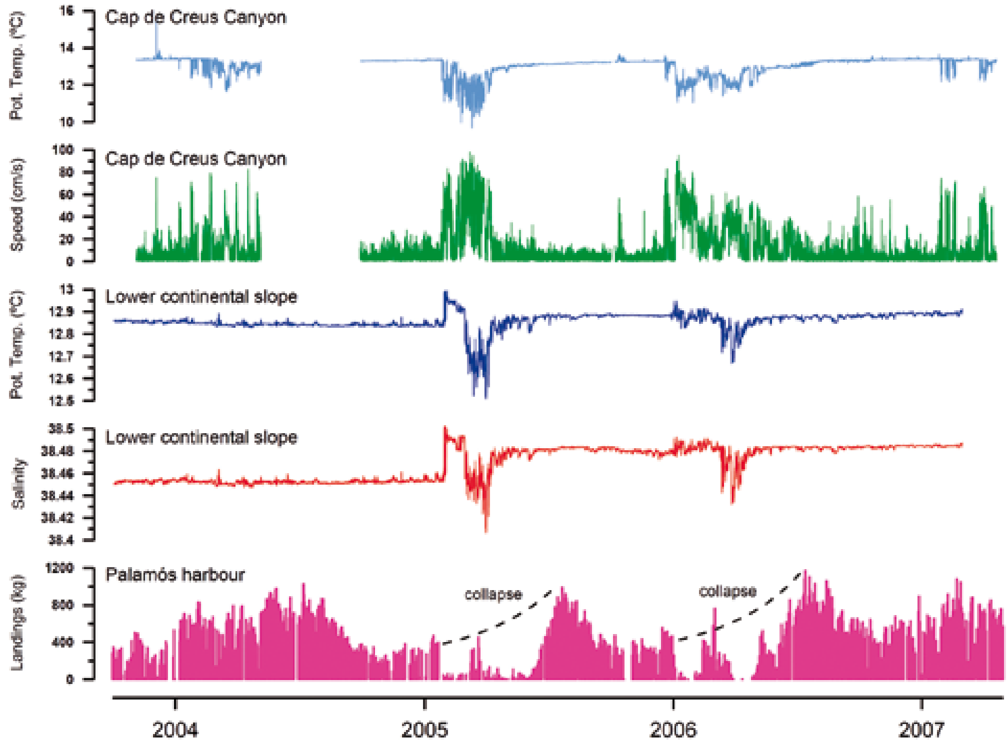

Fig. 6:

Environmental time series and daily catches from late 2003 to spring 2007. Four upper graphs: temperature and current speed at 500 m depth (Cap de Creus canyons); and temperature and salinity at the lower continental slope depths, before, during and after the dense shelf water cascading (DSWC) event of winter 2005 and winter 2006, showing the fishery collapse that encompassed over 6 months. Daily landings of *Aristeus antennatus* at the Palamós harbour are plotted as a violet bar in the bottom chart.

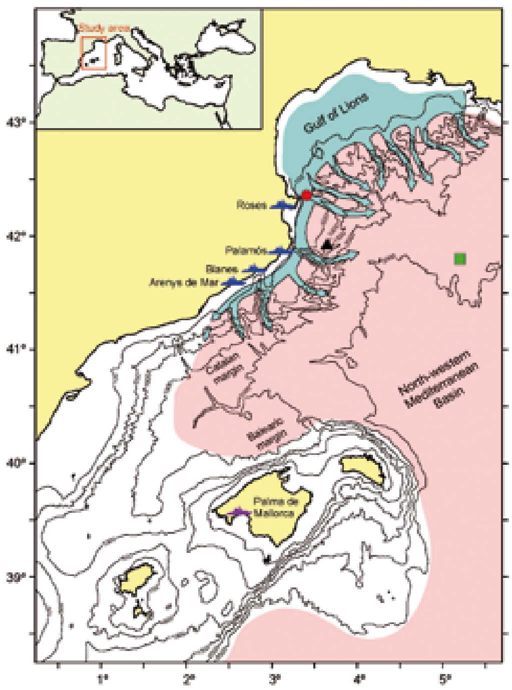

Fig. 7:

Bathymetric map of the northwestern Mediterranean showing the location of the main fishing harbors considered in this case study (blue ships). Pale blue arrows indicate the pathway of the dense shelf water cascading mechanism extending from the Gulf of Lion along and across the continental slope, while the faded pink area represents the region affected by the thermo-haline and turbidity anomaly observed in the Western Mediterranean Deep Water after the 1999 and 2005 major cascading events.

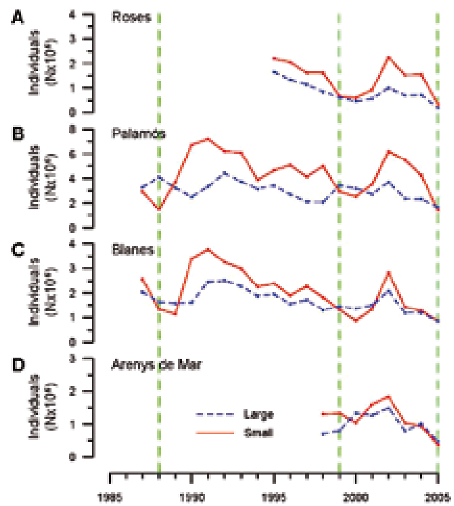

Fig. 8:

Yearly landings at the four most northern harbors of the Catalan cost expressed as number of individuals. Estimation of the abundance of small (continuous red line) and large (dotted blue line) individuals of *Aristeus antennatus* derived from the annual landings in the studied harbors. Green dashed lines indicate the years when major cascading events occurred, i.e. 1988, 1999 and 2005. The temporal evolution of the population structure of *Aristeus antennatus* in all harbors was linked to those cascading events. The number of small individuals increased two and three years after the event, prior to the increase in the number of large individuals, indicating that cascading events enhance the recruitment process of this species.

transport of particulate organic matter from shallower shelf areas associated with cascading thus enhances the recruitment of this deep-sea living resource, reversing the general trend of its over-exploitation (Company *et al.*, 2008).

Settlement and preferential recruitment areas for this species occurs well below 1000 m depth (Sardà *et al.*, 2004). Postlarval individuals (<10 mm CL; carapace length) have only been found at 1200 m depth during winter-time, and juveniles <20 mm CL are only present at non-fishing depths below 1000 m depth. Small juveniles of this species dwell at depths below 1000 m and undertake ontogenetic migrations to shallower grounds (500-900 m) in the canyon heads in the winter period, when fishing mainly takes place for adult populations in all submarine canyons off the Catalan coast.

This climate-driven mechanism of interaction across ecosystems originated in shelf environments and, occurring on a decadal time-scale, controls the biological processes of a deep-sea population and prevents fishery collapse. The physical disturbance originated by strong currents during intense cascading events displaces the individuals of a deep-sea living resource from the fishing grounds inside and around submarine canyons (Fig. 6). However, after 2-3 years, an increase in landings occurs, preceded by an increase in juvenile landings (Fig. 8). Thus, the increases in landings of this species can be explained by an enhancement of its recruitment process favored by the large transport of particulate organic matter to the basin during intense cascading events.

Climate-induced phenomena other than Dense Shelf Water Cascading affect water and sediment transport patterns and thus may have an impact on biological communities. They are related to the occurrence of coastal storms. The Mediterranean Sea is one of the most cyclogenic regions in the northern hemisphere during winter time, and severe weather conditions associated with storm development are common. Associated intense wind, heavy rains, flash floods, high waves and intensified currents commonly cause serious damage along the shoreline, occasionally including loss of human lives. Recently, a unique data set was published showing how one of the most extreme coastal storms of the last decades lashing the Western Mediterranean area, with measured wind gusts of more than 25 m s^{-1} and maximum wave heights over 14 m, rapidly impacted the deep-sea ecosystem in the Blanes submarine canyon (Sanchez-Vidal *et al.*, 2012). In addition to coarse shelf sediment remobilisation, a large reservoir of mostly marine organic carbon associated with fine particles subjected to wave resuspension along the shoreline and on the continental shelf was also mobilized and redistributed across the deep basin. Sanchez-Vidal *et al.* (2012) demonstrate that severe coastal storms are highly efficient in transporting organic carbon from shallow to deep, thus contributing to its sequestration. Thus, and in addition to Dense Shelf Water Cascading, other intermittent natural atmospheric drivers such as coastal storms may have the potential to highly impact the deep-sea ecosystems and their associated living resources.

Effects of trawling on turbidity, sediment transport and accumulation in canyons

Among the anthropogenic activities that can impact the seafloor and remobilize marine sediments, trawling is recognized as the most alarming due to its widespread geographical distribution and recurrent nature. The effect of trawling activities has been a topic of interest in ecology and fishery resource studies because of the impact of gears on benthic ecosystems (Watling and Norse, 1998). That effect recently also become a topic of interest because of its physical impact on muddy grounds of continental shelves and slopes and its consequent effect on the biodiversity of these habitats. The impacts of artificial resuspension on the seafloor tend to be more severe and long-lasting with increasing water depth, owing to the correlative decrease of natural disturbances which can overcome them. Furthermore, impacts associated with trawling may extend down-slope beyond the regions that are actually being fished. This is particularly true in steep environments such as submarine canyons, where previous studies have shown that trawling gears can generate far-reaching sediment gravity flows (Palanques *et al.*, 2006b).

Direct observations by Remote Operated Vehicles (ROV) shows that the continental margin along the Catalan coast is intensely fished down to 900 m depth and consequently presents a high density of trawl tracks (authors' own unpublished data).

Perhaps the most worrying issue is that, following the exhaustion of traditional coastal fisheries, commercial trawling has been progressively extending offshore during the last decades. In this context, the physical effects of trawling in submarine canyons are still poorly known, but recently Palanques *et al.* (2006b) showed the occurrence of a direct relationship between trawling activities, turbidity peaks and sediment flux, which increase during the calm, dry season. These authors also discussed the mechanisms that cause these unexpected increases in sediment transport in the Palamós canyon, and the relevance they have for present-day sediment dynamics.

Due to their peculiar hydrodynamic and biogeochemical features, submarine canyons and their rims harbor considerable biodiversity and faunal abundance and, as a consequence, the soft bottoms surrounding submarine canyons are often targeted by trawlers, which today can even venture within steep canyon walls. The studies conducted in the Palamós submarine canyon documented propagation to the canyon axis of trawling-induced resuspension within the canyon walls (Palanques *et al.*, 2006b) and the imprint of this anthropogenic activity in the deep sedimentary budget (Martin *et al.*, 2008). The Palamós Canyon is, together with Blanes Canyon, the largest submarine canyon in the Catalan margin south of Cap de Creus, and constitutes a remarkable ´hotspot´ for suspended and downward sediment fluxes in this margin (Martin *et al.*, 2006, 2007; Zuñiga *et al.,* 2009). The canyon is deeply incised in the continental shelf and its steep flanks, indented by networks of gullies, favor the active transport (both natural and human-driven) from the continental shelf and upper slope into the deep canyon axis. The canyon area hosts two fishing grounds, one on the northern canyon wall, which is called Sant Sebastià, and one on the southern canyon wall close to the canyon head axis, which is called Rostoll. The trawling fleet operating in the Palamós canyon walls mainly target *Aristeus antennatus* and, as said above, has been very active to depths up to 850 m during the last decades.

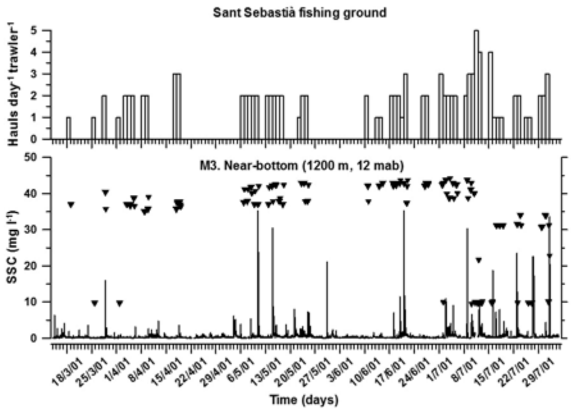

Fig. 9:

Number of hauls per day and per trawler recorded by a fishing vessel specializing in the red deep-sea shrimp *Aristeus antennatus* (adapted from Palanques *et al.*, 2006). The data corresponds to fishing activity in the fishing ground named Sant Sebastià (north canyon wall) in spring and summer 2001 (above). Water turbidity (SSC-suspended sediment concentration) and haul depth in the Sant Sebastià fishing ground in spring and summer 2001 (below).

The number of hauls per day by a single fishing boat and depths where it operates are shown in Fig. 9. The data shows that when the fishing activity is deeper, i.e. during late spring and summer months following the seasonal movements of the red shrimp, the suspended sediment concentration (SSC) in the canyon axis (>400 m deeper than fishing grounds) is correspondingly higher. The mechanism that connects both observations has been identified as sediment-laden flows triggered by the heavy fishing gears, as indicated by simultaneous and abrupt increases in near-bottom downslope current speed and SSC, and by the temporal coincidence of these turbidity peaks with the passage of the fishing fleet along the nearest fishing grounds (Fig. 10). Recent observations have highlighted the fact that these sediment gravity flows triggered by the trawling fleet are produced on a daily basis and during these events SSC increases over natural baselines by up to two orders of magnitude, from the seafloor to a minimum height of 100 m above it (Martin *et al.*, in prep.). It has also been proposed that the cumulative effect of this persistent anthropogenic mechanism of sediment resuspension and transport has resulted in noticeable changes of sediment accumulation rates inside the canyon, particularly since the accelerated industrialization of the fleets in the 1970s (Martin *et al.*, 2008). The ecological consequences of all these human-induced perturbations are compelling and are at present under study.

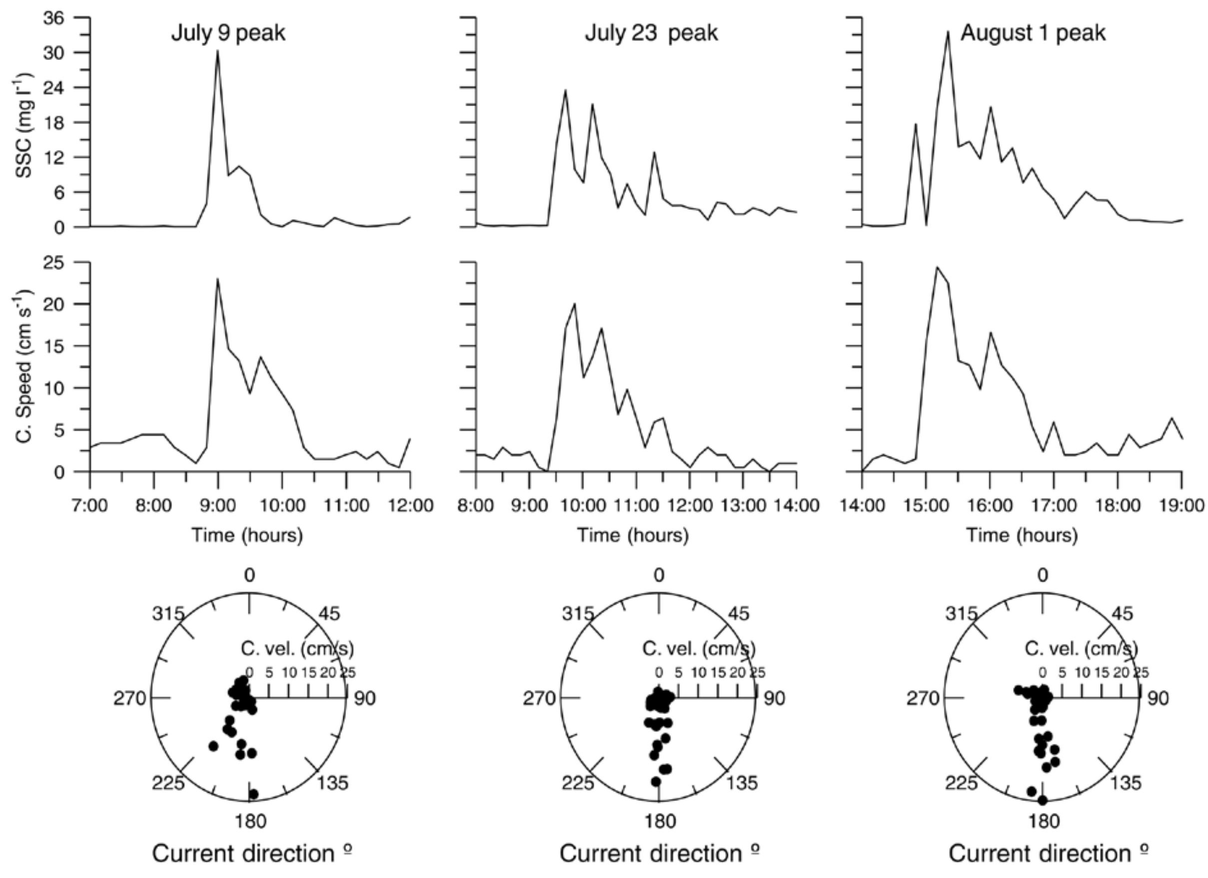

Fig. 10:

Detail of Suspended Sediment Concentration (SSC) peaks, current speed and current direction (in scatter plot) during the main gravity flow events (adapted from Palanques *et al.*, 2006).
Turbidity and downslope current speed increases occurred about 2 h after the fishing fleet crossed the Mongrí gully along the Sant Sebastià fishing ground.

POLLUTION

Marine litter

Fig. 11:

Examples of marine litter collected with an otter trawl during scientific sampling for megafauna in the bathyal northwestern Mediterranean (© Ramirez-Llodra, ICM-CSIC).

The accumulation of marine litter on the deep-sea floor is of increasing concern to the scientific, political and Non Governmental Organization (NGO) communities. The main sources of marine litter include highly inhabited coastal areas (such as the Mediterranean coast), discharges from rivers, illegal dumping from ships, and accidents or natural disasters. The routine dumping of waste from ships was legally banned by the London Convention in 1972 and, in the framework of the Barcelona Convention (1976) for the protection of the Mediterranean Sea against pollution, the Mediterranean countries adopted a protocol in 1980 for the protection of the Mediterranean Sea against pollution from land-based sources (UNEP, 2009). Nevertheless, littering is a persistent problem, with approximately 6.4 million tonnes of litter being dumped in the oceans each year, part of which sinks to bathyal and abyssal depths (Ramírez-Llodra *et al.*, 2010). In the revised version of the Barcelona Convention protocol (1996), marine litter is defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment" (UNEP, 2009).

Although to date most studies of marine litter have been conducted on floating debris, coastal areas and the shelf (Galgani *et al.*, 2000), and information on deep-sea habitats is scarce, some studies are available on bathyal and abyssal habitats and fauna (Galil *et al.*, 1995; Galgani *et al.*, 1996, 1998, 2000, 2010; Watters *et al.*, 2010; Miyake *et al.*, 2011; Ramirez-Llodra *et al.*, in prep.).

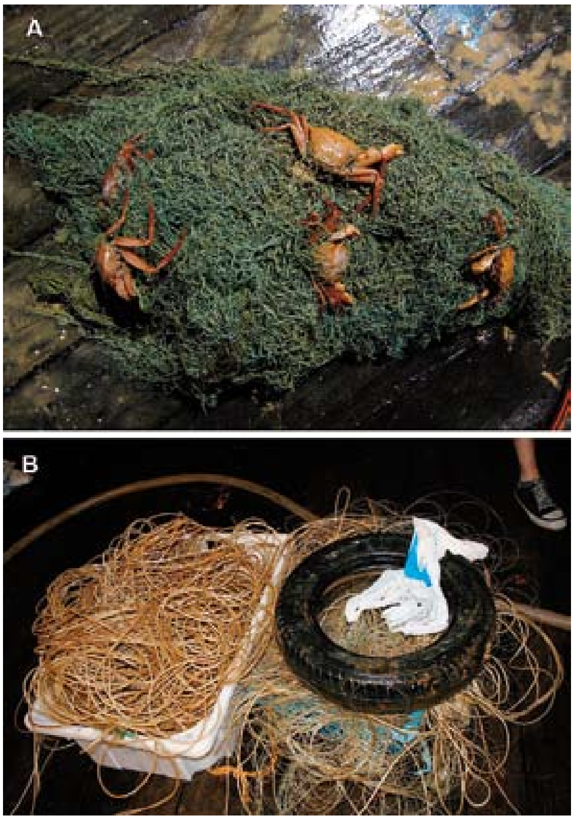

Fig. 12:

Lost or discarded fishing gear collected from the deep Mediterranean Sea. A, example of ghost fishing from a trawl net. B, longline.
(© Ramirez-Llodra, ICM-CSIC).

Recently, the accumulation and distribution of marine litter were quantified during the PROMETEO project, both on the Blanes canyon and adjacent open slope areas at 900 and 1500 m depth, from the otter trawl and Agassiz samples conducted for megafauna. The most abundant litter types found were plastics (e.g., bags, buckets, bottles), glass (e.g., bottles and broken glass) and metal (e.g., tins and cans) (Fig. 11). Clinker, the hard residue of burnt coal from steam ships that operated at the end of the 18^{th} century for 150 years, was found in all samples, often colonized by the brachiopod *Grypheus vitreus*. A wide variety of domestic (e.g. shoes, toothbrushes, a chair) and industrial (e.g. oil drums, tires) waste objects were also collected during the PROMETEO survey, and lost or discarded longlines and fishing nets were also common in the samples.

Although variability in the type and abundance/weight of litter was high amongst samples, preliminary results indicate a trend of accumulation of litter at depth, mostly at the 1500 m sampling site, both in the canyon and on the open slope. Significant differences in litter abundance were not found between the canyon and open slope at comparable depths. Canyons can act as conduits for transport of matter from the shelf to the deep basin, and a higher amount of litter would be expected to be found in the canyon compared to the open slope. However, in our study, we only sampled down to 1500 m depth and therefore we could have missed the flushing effect of canyons, where litter would accumulate at the deeper parts of these marine geological structures, below 2000 m depth (Ramirez-Llodra *et al.*, in prep.). A study of marine debris in the Gulf of Lion (NW Mediterranean) showed that only small quantities of litter were found on the shelf, while most of the litter was found on the canyon and bathyal plain, and that up to 90% of the litter was plastics of various sorts (Galgani *et al.*, 1996). The accumulation of litter in certain areas has been related to the proximity of large cities, the topographic characteristics of the seafloor (e.g. canyons, rocks, crevasses) and hydrographic conditions (Galgani *et al.*, 1996, 2000).

The effects of marine litter on the habitat and fauna are still poorly understood, but they include suffocation of animals, physical damage of fragile communities such as cold-water corals or sponges, ingestion of small litter particles and microplastics, toxicity from paint chips or persistent organic pollutants (see below) and ghost fishing from lost or discarded fishing gear. Evidence of ghost fishing was provided by a net collected from the NW Mediterranean seafloor at 2000 m depth which contained several dead and moribund *Geryon* crabs (Fig. 12). Further dedicated studies following standardized methods are essential to provide a clear picture of litter distribution on the seafloor and to describe the effects of this litter on deep-sea habitats and their fauna. The results will provide crucial data to address the marine litter problem and propose solutions.

Chemical pollutants

In recent years there has been growing awareness that the deep-sea is not as pristine as often presumed and that it may actually act as a global sink for persistent contaminants that enter the marine environment (Ballschmiter *et al.*, 1997). Due to their shape and proximity to the coastline, submarine canyons have been shown to act as natural conduits for organic and particulate matter, including sediment-associated anthropogenic contaminants, transported from coastal areas to the deep-sea (Puig *et al.*, 1999; Paull *et al.*, 2002; Hartwell, 2008; Palanques *et al.*, 2008; Richter *et al.*, 2009; Jesus *et al.*, 2010). In particular, persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDTs) could be of major concern because of their high lipophilicity, persistence and toxicity. In the NW Mediterranean Sea, POPs have been found to bioaccumulate in a number of deep-sea organisms (García *et al.*, 2000; Porte *et al.*, 2000; Solé *et al.*, 2001; Borghi and Porte, 2002), but knowledge on the impact of anthropogenic contaminants on deep-sea ecosystems is still limited. Findings from a previous study indicated that fish caught inside the Blanes submarine canyon were exposed to higher contaminant levels compared to individuals from the adjacent open slope, although this trend was not reflected in the chemical body burden analysis of these same organisms (Solé *et al.*, 2009). Furthermore, in a more recent study conducted within the framework of the PROMETEO project (Koenig *et al.*, submitted), the combined analysis of chemical and biochemical parameters seemed to support these initial findings. Higher POP levels in muscle tissue and induced xenobiotic metabolism and antioxidant responses in the liver/hepatopancreas were observed in a fish and a crustacean species, indicating that animals within Blanes Canyon were exposed to higher contaminant levels (Fig. 13).

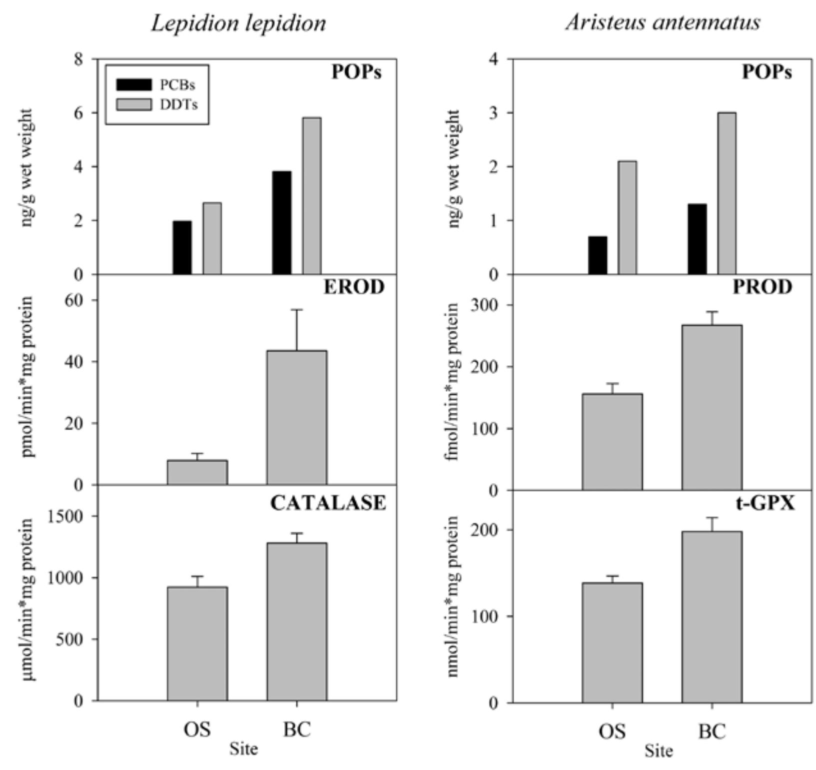

Fig. 13:

Contrast between samples from open slope (OS) and Blanes canyon (BC) of *Lepidion lepidion* and *Aristeus antennatus* at 900 m. Reported results include persistent organic pollutant (POP) levels (ΣPCBs and ΣDDTs) in muscle tissue and hepatic biomarker responses cytochrome P450 (EROD or PROD), and antioxidant (CAT or GPX) enzyme activities.

However, results also indicated that the accumulation of POPs within the canyon may be subject to spatial and temporal fluctuations. Because of the lipophilic nature of POPs, these compounds tend to bind to suspended particles in the water column and be transported along with them. Hence, the spatial and temporal distribution patterns of POPs are likely to be influenced by the periodicity and amplitude of sediment transportation and re-suspension processes. Higher pollution loads may thus be transferred to the canyon during local meteorological forcing events, which are known to principally occur from late autumn until early spring (Heussner *et al.*, 2006; Zúñiga *et al.*, 2009). Moreover, contaminant accumulation appears to be more important at the head of Blanes canyon (900 m) than at greater depths (1500 m). This can be explained by the fact that, as shown by previous studies, the propagation of mass fluxes within the canyon axis depends on the magnitude of these episodic events (Zúñiga *et al.*, 2009). Hence, it is possible that storms of relatively short duration result in higher sedimentation rates at shallower depths, while events of greater intensity such as dense-shelf water cascading (DSWC) could cause a transfer of larger amounts of material from the upper canyon regions to the deep-sea (Canals *et al.*, 2006; Palanques *et al.*, 2006a; Zúñiga *et al.*, 2009; Sanchez-Vidal *et al.,* 2012).

The head of the canyon may thus act as a temporary trap for organic contaminants, which are episodically transferred to greater depths during major storm events that flush the canyon, propagating throughout the northwestern Mediterranean deep-sea basin (Canals *et al.*, 2006; Company *et al.*, 2008). Consequently, species inhabiting submarine canyon ecosystems may be at risk of experiencing higher levels of exposure to anthropogenic contaminants and consequent pollutant-induced adverse effects. It is important to further investigate the role of submarine canyons in the transport of organic contaminants from surface waters to the deep-sea and the potential impact this may have on organisms dwelling within the canyon.

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